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Cage Mode Propagation Experiments

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Several experiments have been performed wherein an electron beam is propagated inside an array of four parallel conducting rods which form the long sides of a slender box. The electron beam is injected at one small face of the box and the other small face is the beam dump. This configuration is referred to as a cage. Various combinations of parallel and angled injection of the beam, metal and resistive rods, and different background pressures of Nitrogen were tried. Diagnostics included still photography, a beam current monitor at the injection point, and a net current monitor at the beam dump. The effect of the cage was always to restrict hose motion and enhance beam transport.

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SYNOPSIS

A series of experiments were performed demonstrating that a four conductor cage embedded in a background gas (.5 to 40 Torr of Nitrogen) could guide the head of an electron beam and limit hosing in the body of the beam. Since the experiments were performed during spare time on the Pulserad accelerator (1.4 MV, 10 kA, 25 ns) they were done in a simple way. Metal rods and long resistors were used in place of laser induced conductive channels to form the cage. The diagnostics were still cameras and current monitors.

The cage resistances (1.2 ohms/cm, each rod) were well within the theoretical limits for guidance and stability (10 ohms/cm, each channel). The positive results thus demonstrate the robustness of the effect in this regime, particularly as the beam was not highly conditioned. A number of effects (spiraling and hollowing) were apparently seen whose exact nature could not be determined with the diagnostics employed.

CAGE MODE PROPAGATION EXPERIMENTS

INTRODUCTION

We have conducted several preliminary cage mode propagation experiments using the Pulserad-310 e-beam generator and using solid return current conductors in place of laser-made channels. Our intent was to study the beam dynamics rather than to consider the laser system. These experiments were performed during 1984 and 1985 as spare machine time was available. The situations considered included angled and aligned injection of the e-beam into a highly conducting cage, aligned injection into a resistive cage, and, for comparison, injection into a large diameter metal drift tube. The experiments covered a range of gas pressures.

APPARATUS

The several apparatus used in these experiments are shown in Fig. 1. In all experiments the e-beam emerging from the diode first passed through an aluminum transport tube 0.5 m long with a 3.5° (half angle) taper and a 2.3 cm exit hole. The beam entered and exited through .038 mm thick titanium foils and the tube was filled with 20 Torr of N_2. The principal effect of the transport tube was to remove low energy electrons. The emerging beam stopped and started at $\sim .5$ MeV. The rise and fall times for both the current and voltage were ~ 10 ns. The peak values of voltage and current were ~ 1.4 MeV and ~ 10 kA. Near peak values were maintained for ~ 15 ns so that the FWHM of the pulse was ~ 25 ns.

Five different configurations were used to study the propagation of the beam after it emerged from the transport tube. They are designated as "a" through "e" below:

(a) As shown in Fig. 1-a, a set of four 1.27 cm diameter copper bars, each 1.3 m long, placed parallel to one another at the corners of a square 3.6 cm on a side. The beam was injected at one end of the cage on center but at a 6° angle to the bars. The bars connected electrically to the entrance foil and to a brass beam stop. This array was enclosed in a 60 cm diameter fiberglass tube so that any pressure and gas composition could be introduced.

(b) As shown in Fig. 1-b, the same configuration as in 1-a but with the beam injected parallel to the rods and with an evacuated Faraday cup built into the beam stop. The length of the cage was adjustable so that the transmitted beam current could be measured as a function of length.

(c) As shown in Fig. 1-c, a set of four 1.9 cm diameter copper bars each 1.2 m long and set parallel to one another at the corners of a square 10 cm on a side. The beam was injected on center and parallel to the bars. The bars connected electrically to the entrance foil and to a brass beam stop and were enclosed by the fiberglass tube. The principal distinction between this configuration and that in 1-b is the transverse dimensions of the cage.

(d) As shown in Fig. 1-d, a set of four resistive bars, geometrically identical to 1-c but possessing a resistance of 1.2 Ω/cm each. A Rogowski coil was set just inside the bars where they connected to the beam stop to measure the transmitted net current.

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(e)   As shown in Fig. 1-e, a 60 cm diameter, 1.5 m long metal drift tube ending in a brass end plate. The same Rogowski coil as in (d) was attached to the center of the brass end plate.

In addition to the Faraday cup and Rogowski coil mentioned above, open shutter white light cameras viewed all the configurations both side-on and nearly end-on, while a Frost monitor measured the injected beam current on every shot.

RESULTS

Using the "a" configuration with the angled injection, shots were taken in dry air at pressures ranging from 40 μ to 40 Torr. The results of this experiment are given in Table 1. Above 200 μ, the cage was able to partially capture and guide the beam through the 6° deflection angle.

Table I

Pressure	Behavior seen in the photographs
40 μ	Immediate expansion and dispersal of the beam.
200 μ	A typical, tightly pinched IFR beam surrounded by "feathers" of plasma light. The beam followed the cage for ~.5 m before escaping suddenly between two bars at a ~30° angle.
500 μ	Sprays of beam were lost between the bars immediately upon injection but the brightest part of the beam followed the cage for the full 1.3 m.
1 Torr	Similar to the 500 μ result but with slight hosing of the captured beam within the confines of the cage.
5 Torr	Same as above but with stronger confined hosing (See Fig. 2)
20 Torr	Still shorter wavelength and larger amplitude hosing.
40 Torr	Violent confined hosing. Slight wisps of beam are lost between the bars at the extremity of each beam excursion. (See Fig. 3)

The "b" configuration was used at 500 μ, 5 Torr, and 40 Torr to measure the ratio of peak transmitted beam current to peak injected beam current as a function of cage length. Five shots were taken for each length and pressure and were averaged to give the data points shown in Fig. 4. In all cases there was a large initial loss of beam current at injection. For 500 μ and 40 Torr there were further losses, but at 5 Torr there was no loss over the remaining distance.

The "c" configuration was investigated for 1, 5, 15 and 40 Torr pressures. The results are summarized in Table II. The use of a larger cage should reduce its ability to stabilize (and guide) the beam. A comparison of the open shutter photographs from (b) and (c) supports this prediction. A more surprising feature of the photographs is the apparent separation of the beam into a straight "hollow" component and a "solid" hosing component which spirals outside the hollow component. Whether this separation is real or an artifact of open shutter photography remains unclear.

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Table II

Pressure	Behavior seen in the photographs
1 Torr	Sprays of beam are lost at injection. The remainder of the beam propagates in a stable manner and has a hollow appearance.
5 Torr	There appear to be two propagating components, a straight hollow component and a solid hosing component spiral wrapped around the first component.
15 Torr	Greater hosing by the solid component portions of which are lost between the bars after ~0.5 m.
40 Torr	Only a solid beam is apparent which hoses violently and escapes through the bars at several locations.

A photographic comparison was made between propagation in the resistive cage "d" and the large diameter drift tube. Table III describes the effect of the resistive cage. Table IV describes the effect of the large diameter drift tube. Propagation is always better in the cage at pressures above a few Torr. The formation of a hollow beam component is again apparent above 5 Torr in the cage.

Table III

Pressure	Behavior seen in the photographs
500 μ	The beam propagates within the cage with a slight hosing. Feathers surround the beam and glow around the resistors indicates they may be shorted by plasma.
750 μ	Less hosing and less resistor glow.
1 Torr	Large spray losses occur near the injection point but a portion of the beam appears to pinch together after ~.2 m of propagation and thereafter follow the cage.
5 Torr	Large losses near the injection point but a faint hollow component follows the cage.
15 Torr	Large losses near the injection point but a faint hollow component follows the cage.
40 Torr	Only a solid component is apparent which hoses violently and escapes through the bars at several locations.
> 40 Torr	Near total loss of the beam at injection.

Table IV

Pressure	Behavior seen in the photographs
500 μ	A well pinched and feathered IFR beam with a modest hosing
1 Torr	Relatively straight propagation
$>$ 5 Torr	Violent hose

The final experiment was a comparison of the net current for propagation in the resistive cage configuration "d", and in the large diameter drift tube "e". The beam current at injection was measured by the Frost monitor, and the transmitted net current was measured by the Rowgowski coil attached to the beam stop. Figure 5 shows the injected beam current and transmitted net current in 10 Torr of N_2 for both configurations. In both cases only the head of the beam is received by the Rogowski coil; the body is lost.

Figure 6 shows the same data for 15 Torr of N_2. The head of the beam still propagates in the resistive cage, but very little intercepts the Rogowski coil in the tube.

Figure 7 shows the data for 25 Torr of N_2, and again the head of the beam propagates in the cage but not in the tube.

Results at 40 Torr were similar to those at 25 Torr.

CONCLUSION

The experiments demonstrated that a four-conductor cage can both guide and partially stabilize a relativistic electron beam propagating through dense gas. The 1.4 MeV Pulse-Rad beam was successfully deflected and guided through angles as large as 6°. Higher deflection angles were not possible with the present apparatus. As was expected, the guidance and stabilization were principally effective only near the beam head; the tail of a highly unstable beam is still lost with or without the cage.

Although the experiments successfully demonstrated both tracking and partial stabilization of the beam, further work is required to assess the overall utility of this mode. Theoretical analysis[1] indicates that a resistive hollow channel (cage or smooth annulus) can guide and stabilize a beam propagating in dense gas only if several conditions are met: the hollow channel should encircle the entire beam; the channel conductivity should be high ($> 10^9 S^{-1}$); and the channel resistance should be low (< 10 Ω/cm). Although all of these conditions were initially met in the present experiments, none was actually shown to be required.

Further work is also required to understand whether the beam head does or does not hollow. Although a cage could conceivably act as an emittance filter by rejecting beam electrons with high transverse momenta, the formation of a hollow beam (due to ejection or hosing of low-emittance electrons) seems unlikely. Replacing the open shutter photographs, which are difficult to interpret, with time-resolved diagnostics could well show that the beam does not actually hollow but rather rapidly spirals inside the cage to give the appearance of a hollow beam. High-frequency spiraling is more likely in the beam tail, while low-frequency spiraling is more likely in the beam head.

The last issue not investigated was whether laser-produced channels would work as well as solid resistive rods. This question has been partially answered by the work of Leifeste, et al.[2] who used a 100 mJ, Nd:YAG laser to create hollow channels in low-pressure nitrogen doped with diethylanaline. Successful electron beam guidance was obtained at gas pressures below 1 Torr. Above 1 Torr the laser ionization was too low to produce an effective channel. The use of solid resistive rods in the present

experiment eliminates the need for a high-power laser, permits effective channels to be readily generated even at high gas pressures, and should in principle produce the same results as an equivalent, gaseous conductivity channel.

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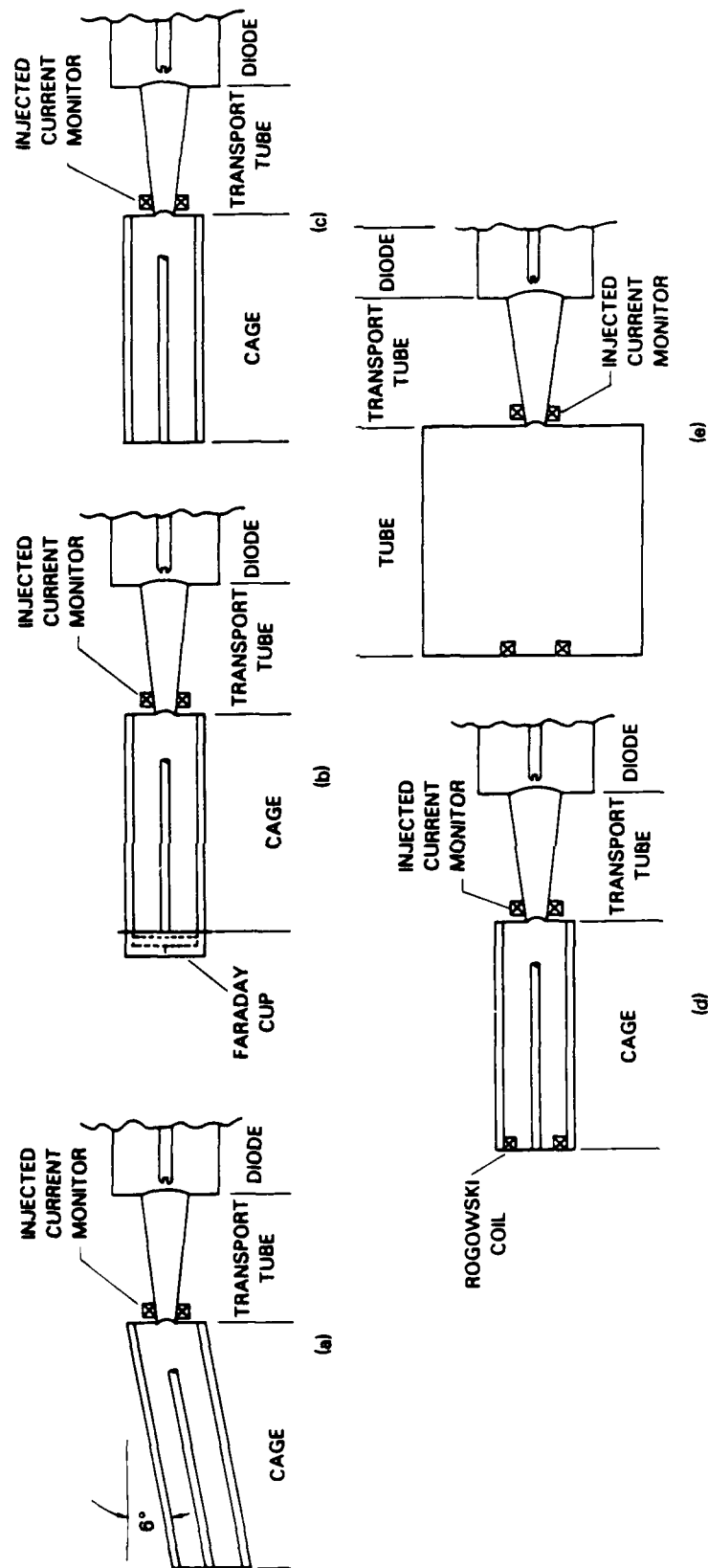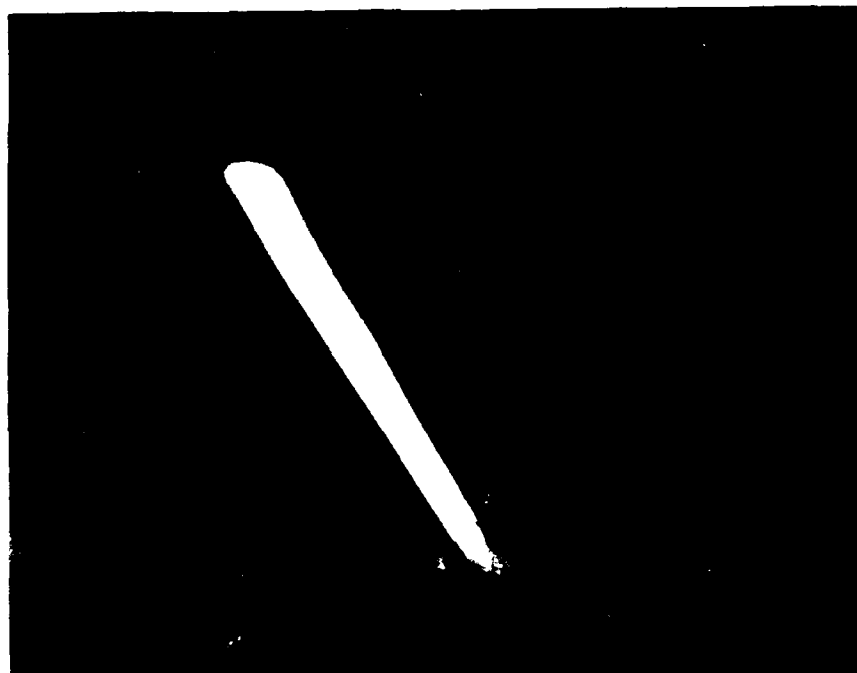2. G.T. Leifeste, C.A. Frost, R.B. Miller, C. Ekdahl and C. Crist, *Bull. Amer. Phys. Soc.* **29**, 1292 (1984).
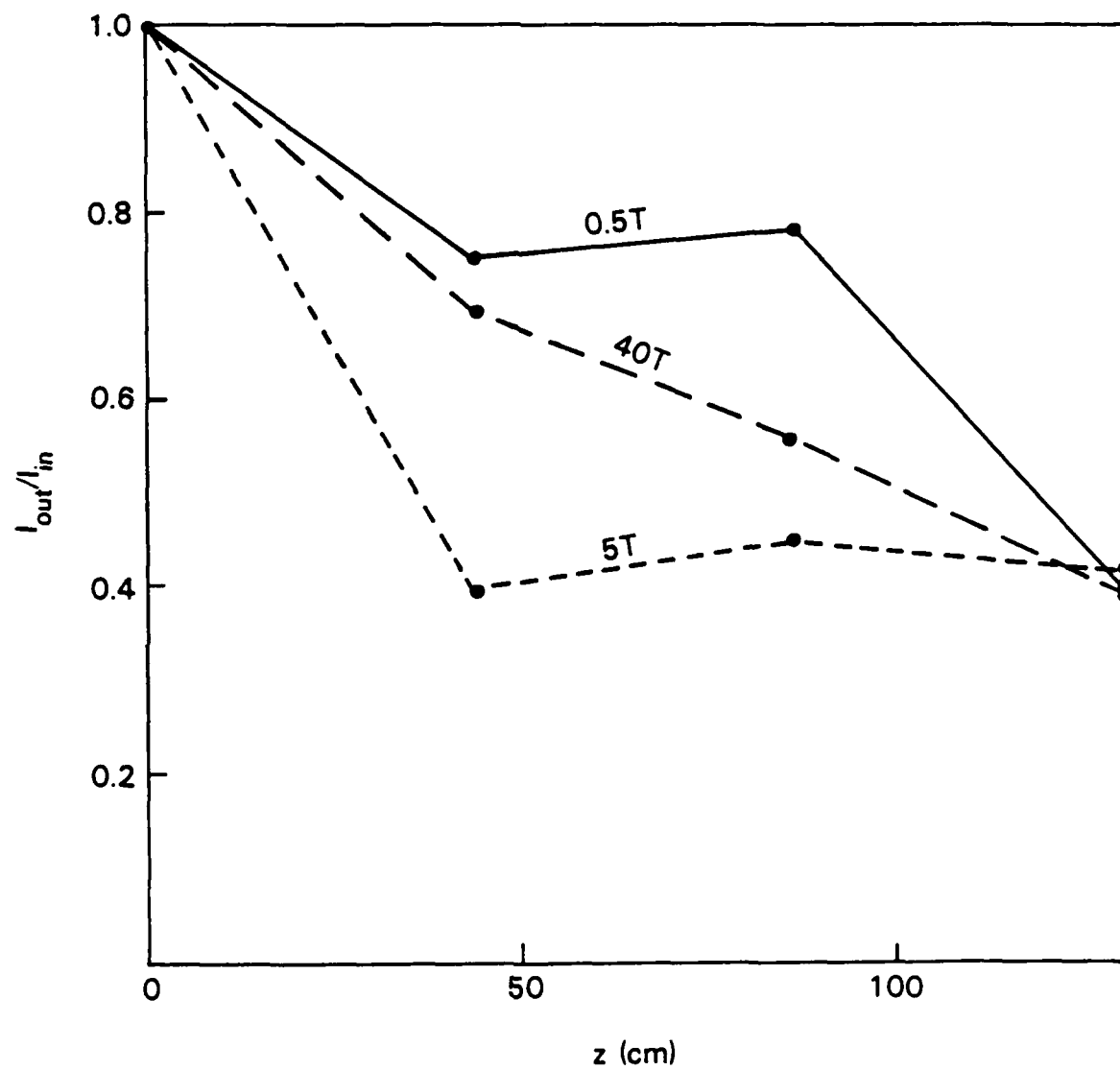
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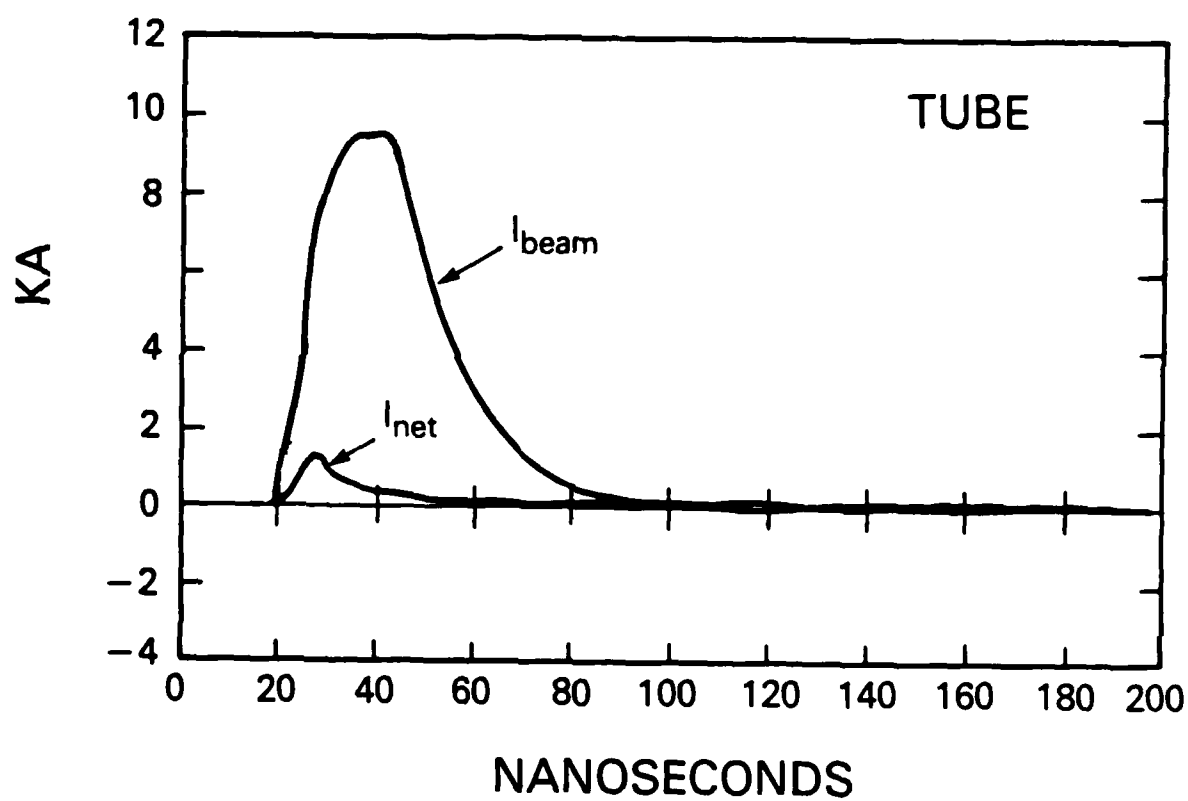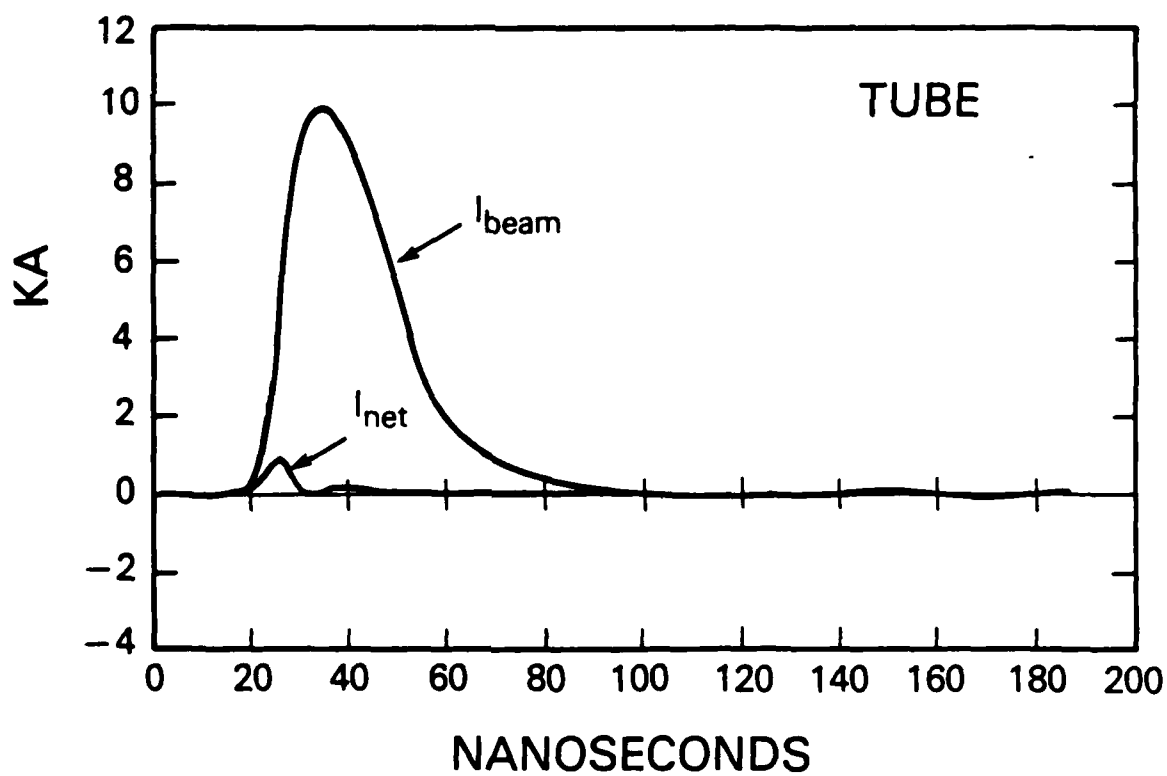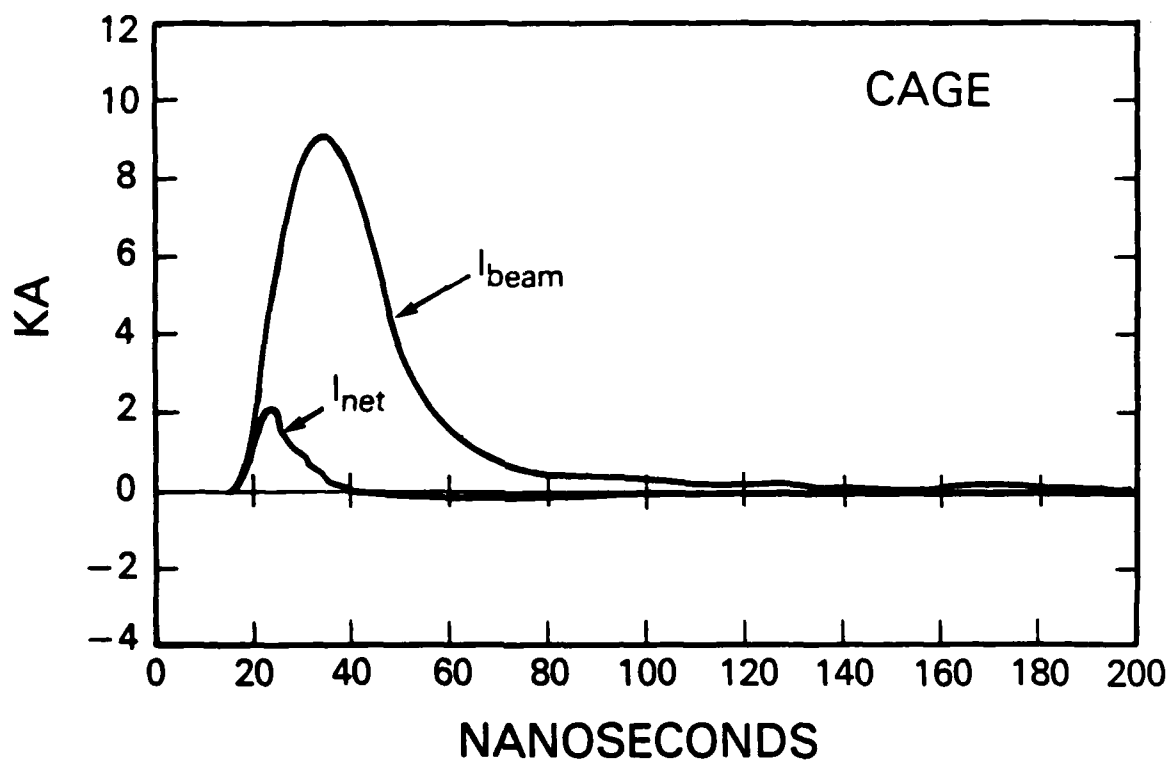Figure 5

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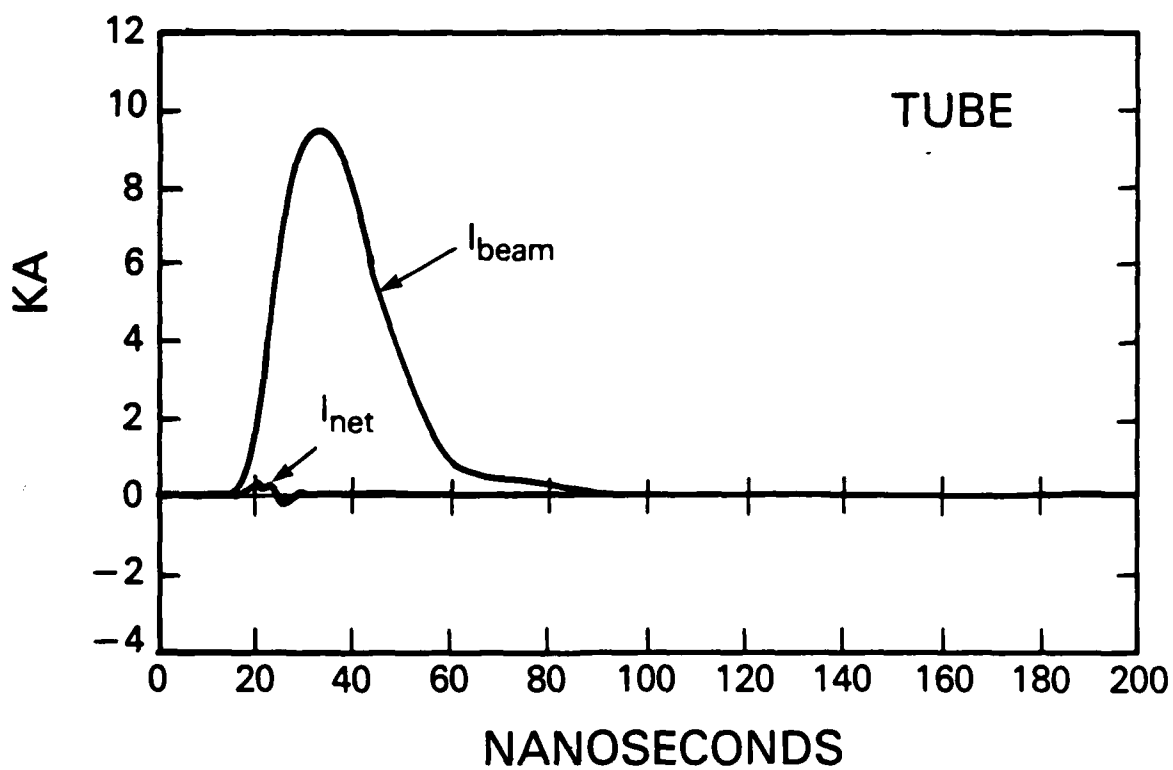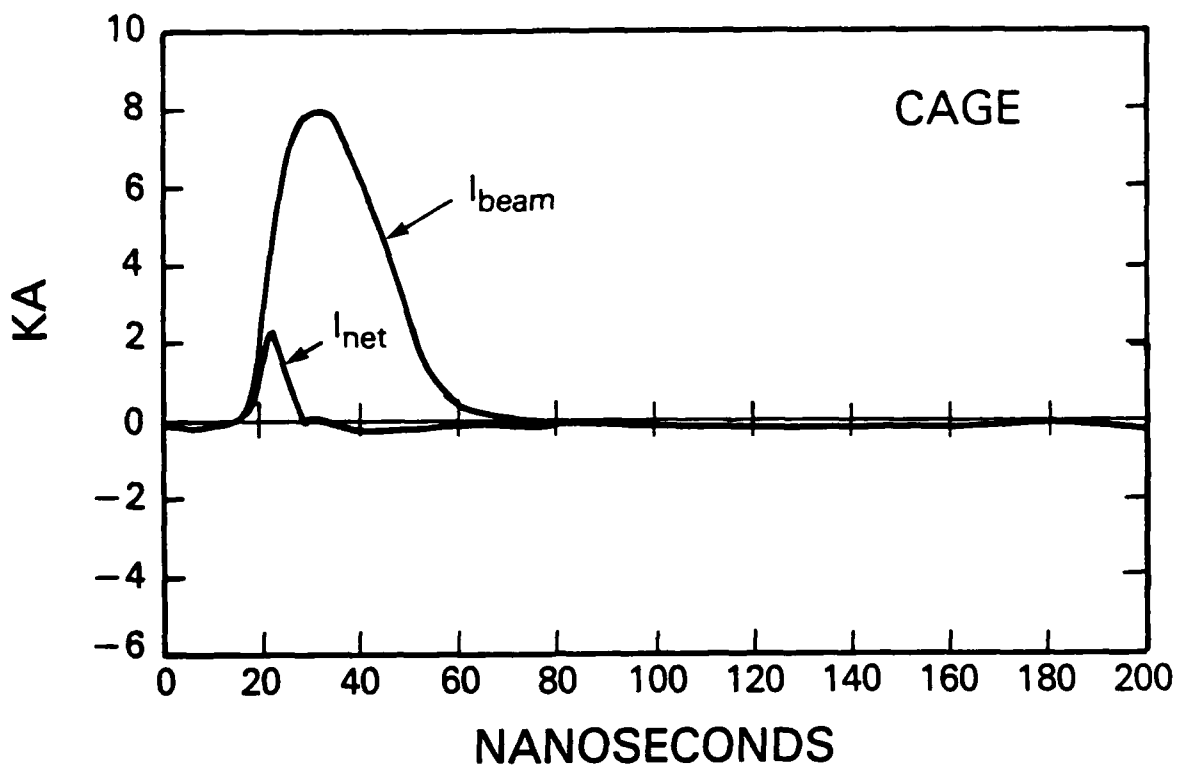
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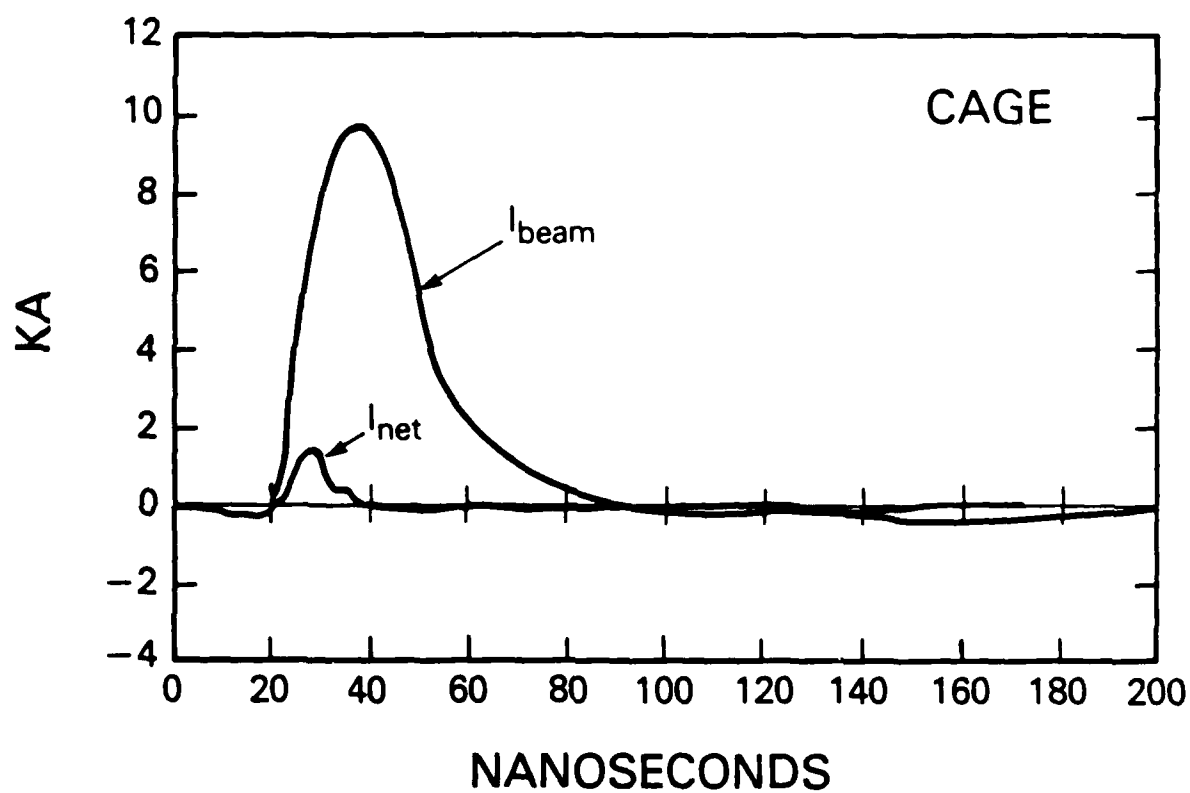
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